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(54) Title: APPARATUS FOR RECEIVING RANGING SIGNALS
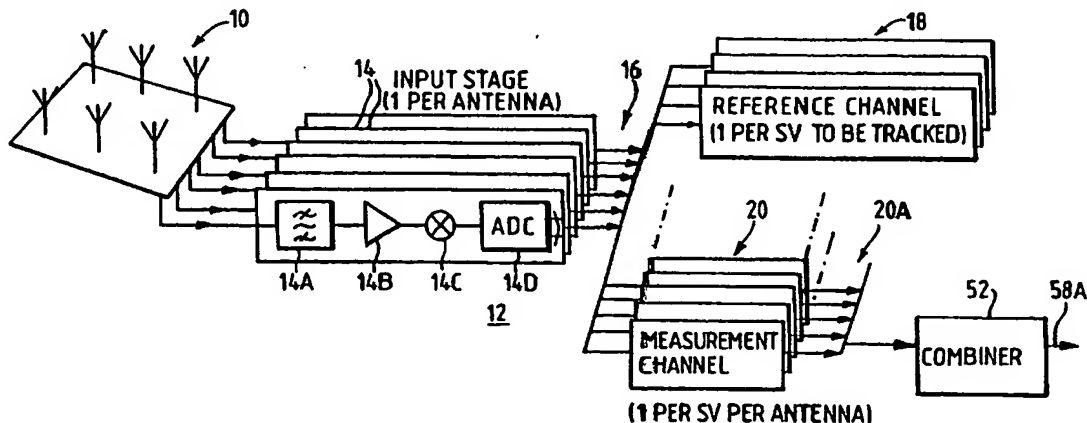
(57) Abstract: Apparatus for receiving ranging signals (e.g. signals from Grobal Positioning System satellites) has a receiver cou-
pled to a plurality of spaced antennas (10). The receiver includes a signal combiner (62) which receives, from a processing circuit,
signal components individually representative of a characteristic of th received ranging signals (e.g. signal-to-noise ratio) at a respec-
tive antenna and weights the said compenents to produce a range estimate of improved accuracy in difficult reception conditions. In
one embodiment the receiver includes a common i.f. channel which filters a combination signal representative of all the incoming
signals in order substantially to maintain phase coherence between the incoming signals, yielding improvements in carrier phase
measurement and discrimination.

Apparatus for Receiving Ranging Signals

This invention relates to apparatus for receiving ranging signals produced by a plurality
of remote transmitters which form part of a universal ranging system such as a satellite
5   positioning system, for example, the Global Positioning System (GPS).

The original concept of GPS envisaged user equipment with an antenna having a
largely clear view of the sky, whether mounted on aircraft, ships, land vehicles or in
portable applications. Increasingly, however, there are requirements for GPS receivers
10   capable of operating in poor signal conditions and which operate at higher than
previously accepted accuracies. Weak signal conditions in ranging systems such as the
GPS satellite-based system, are usually caused by obstructions or multipath
propagation. Such reception conditions often occur inside buildings, but also outdoors
in densely built-up areas or under foliage. The region over which a GPS receiver can be
15   expected to operate can be improved by maximising the received power-to-noise ratio
for each satellite signal.

Signal reception of GPS inside buildings is characterised by a transmission model that
has no dominant mode since most signals arrive at the receiver after one or more
20   reflections. This transmission model implies that the signal has Rayleigh fading
statistics. Such statistics are generally found when there are multiple signal paths to the
receiver, each model allows the Central Limit Theorem to be invoked to describe signal
amplitude. The magnitude of the resulting signal, free of signal phase measurements,
may then be established as a two-dimensional normally distributed random variable.
25   The magnitude is a first order χ^2 distribution with the characteristic Rayleigh
probability density function:

$$P(R) = (R/\sigma^2) \, exp(-R/2\sigma^2)$$

The direction of the signal arrival is not well defined in this transmission model and
may come from any direction. In reality, this will be constrained by physical factors
30   such as nearby windows capable of GPS signal transmission. For the most part, it will
also not be possible to determine the polarisation of the signal. GPS satellite

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transmissions are right-hand circularly polarised but become circularly or elliptically polarised on reflection from metallic objects.

In the circumstances described above, the signal field can be subject to deep fades,
5   similar to those experienced by FM radio receivers in automotive environments.

Another difficulty is the shrinking physical size of GPS receivers bringing, amongst other problems, the danger of self-jamming due to electromagnetic noise from small devices with large gate counts exceeding local thermal noise levels. In addition, the
10   external electromagnetic environment is deteriorating as a result of increasing congestion in the electromagnetic spectrum. As an example, digital broadcast television, which is due to expand rapidly in coming years, has relatively high out-of-band emissions compared with previous systems. Other satellite communication services are being allocated spectrum space in bands adjacent GPS frequencies.
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This invention aims to counter such difficulties by providing a receiver system having a plurality of antennas. According to a first aspect of the invention, apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system comprises a radio receiver unit having a plurality of radio
20   frequency (r.f.) input connections, and a plurality of spaced-apart antennas each connected to a respective said input connection, wherein the receiver unit includes: an antenna signal processing circuit responsive to the ranging signals for producing output signals including components each individually representative of at least one characteristic of the ranging signals received at a respective antenna; and a signal
25   combiner configured to receive the output signals, to monitor, for each of a plurality of the said remote transmitters, at least one characteristic of the ranging signals from that remote transmitter via the different antennas, and to weight one or more of the said components to yield a range estimate.

30   According to a second aspect of the invention, apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system comprises a radio receiver unit having a plurality of radio frequency

(r.f.) input connections, and a plurality of spaced-apart antennas each connected to a respective said input connection, wherein the receiver unit includes: an antenna signal processing circuit responsive to the ranging signals for producing output signals including components each individually representative of at least one characteristic of

5   the ranging signals received at a respective antenna; and has a receiver unit with a signal selection arrangement configured to receive the output signals, to monitor, for each of a plurality of the said remote transmitters, at least one characteristic of the ranging signals from that remote transmitter via the different antennas, and to select one or more of the said components to yield a range estimate.

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The signal combiner or selection arrangement is preferably configured to weight or select the components according to the signal-to-noise ratios of the ranging signals received from at least one of the transmitters, advantageously from each of them. Alternatively, or in addition, the signal combiner or selection arrangement may be

15   configured to weight or select the components according to the amplitudes of the ranging signals whether from one or several of the transmitters.

Typically, the antenna signal processing circuit includes at least one code-tracking loop for tracking code modulation of the ranging signals when received by the antennas. The

20   selection may be performed periodically so as to select one of the ranging signals the amplitude of which is greater than the others, and then to apply the selected signal to the code tracking loop. There may be a number of code tracking loops, the signal selection arrangement being configured periodically to select a number of the ranging signals by weighting the magnitudes according to a predetermined weighting scheme

25   which is dynamically variable, being adapted to the changing electromagnetic conditions as happens, for instance, when a motor vehicle containing the apparatus passes through a built-up area.

In the last-mentioned situation, the changing electromagnetic environment is largely

30   due to varying intensities of signals reflected from adjacent buildings. Thus, the signal combiner or selection arrangement may be specifically configured to weight or select

the components due to signals from the different antennas according to their multi-path content.

As an alternative to using a code-tracking loop for tracking code modulation of the ranging signals, a parallel correlator structure may be used.

Although, in the case of GPS, code-tracking may be relied upon to provide position fixes, improved accuracy may be obtained by measuring carrier phase. In the context of the present invention, a receiver unit including a carrier phase tracking loop may include a phase-shifting arrangement operable to apply a selected phase shift to a selected or weighted signal, the magnitude of the phase shift being dynamically adjusted according to the antenna via which the selected or weighted signal is received. Accordingly, it is possible to configure the phase-shifting arrangement to adjust the phase shift in a manner that maintains coherent phase matching between ranging signals received via the different antennas to improve phase tracking accuracy. Coherent phase tracking may be maintained in order to allow switching between different selected ranging signals from different antennas.

Phase and amplitude taper multiplication coefficients may be applied to the ranging signals from the different antennas using, for instance, an adaptive equaliser. Phase taper, then, can cause the ranging signals received at different antenna elements from a particular direction to reinforce each other, giving a means of selecting signals from a particular direction (e.g. from a particular transmitter), and for rejecting signals received from other directions, e.g. due to unwanted reflections or other sources of interference. An amplitude taper can act as a spatial filter altering the combined beam pattern of the antennas as an array.

According to a third aspect of the invention, apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system comprises a radio receiver unit having a plurality of r.f. input channels and a plurality of spaced-apart antennas each connected to a respective said input channel, wherein: the receiver unit includes at least one antenna signal processing

circuit responsive to the carrier phases of the ranging signals received via at least one of the antennas; each input channel i includes a multiplying element arranged to combine a respective first multiplier signal M_i with an incoming signal in the channel, the multiplier signals constituting an orthogonal set of signals; and the receiver unit further

5   includes a combining element for combining the multiplier output signals resulting from combining the incoming signals with the multiplier signals, a common intermediate frequency channel including common filtering means for receiving the multiplier output signals from the combining element, an analogue-to-digital converter (ADC) coupled to an output of the common channel, and a processor for applying

10   second multiplier signals to a digitised signal obtained from the ADC thereby substantially to isolate from each other signals representative of respective incoming signals from respective antennas, each second multiplier signal corresponding to or being the same as the first multiplier signal for the respective antenna; whereby phase coherence is maintained between the different signals associated with the different

15   antennas.

In such apparatus, as well as apparatus as described above in accordance with the first and second aspects of the invention, the antennas may have different polarisation characteristics, the processor being programmed to combine digitised representations of

20   the different antenna signals to weight or select received signals having a predetermined polarisation. The antennas may comprise a pair of antennas each formed as a linear element, the linear elements being arranged perpendicularly to each other so that, according to the way in which the digitised representations of the signals are combined, the receiver unit selects received signals of right-hand circular polarisation or left-hand

25   circular polarisation. By arranging for the processor to be programmed to weight and combine the digitised representations of the different antenna signals, it is possible to select received signals of elliptical polarisation. In such cases, the processor is preferably configured to implement sum and difference networks. The digitised representations may be combined variably, e.g. in an adaptively varying manner in

30   order to optimise signal reception in a multipath environment.

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The processor may be programmed, in addition, to apply selected weightings to the signals isolated after passing through a common channel in the receiver unit in order to tailor the response of the receiver unit to favour received signals having a predetermined characteristic. Such weightings may be adaptively variable.

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In preferred apparatus having a common channel for signals representative of incoming signals from a plurality of different antennas, the receiver unit may have input channels which include a pair of sub-channels for I and Q components of each respective incoming signal, the processor being programmed to combine the I and Q components

10   after the isolation step.

CDMA techniques may be used in the receiver unit to combine signals received from individual transmitters at different antennas in order to feed them through a common channel which maintains phase coherence and which, in particular, can filter signals

15   with a constant group delay and, then, subsequently to separate them for further processing. Accordingly, the receiver unit may include a multiplying combiner stage for each channel which multiplies the incoming signal from each antenna by a spreading code assigned to that antenna. The signals may then be combined by adding and feeding them through the common channel. Corresponding despreading codes may

20   be applied at the end of the common channel in order to separate the signals representative of the incoming signals from different antennas. The spreading and despreading codes may be signals constituting an orthogonal set, as mentioned above.

It will be appreciated that much of the receiver architecture may be implemented in

25   software. There is also a choice as to the point in the receiver chain at which analogue signals are converted to digital form. Thereafter, processing may take place by hardwired logic or software processing. It will also be appreciated that the references to channels above include virtual channels whereby circuitry is shared between channels on a multiplexed basis or where different channels are formed in the software routines.

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According to a further aspect of the invention, apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal

ranging system comprises a radio receiver unit having a plurality of radio-frequency (r.f.) input channels, and a plurality of spaced-apart antennas each connected to a respective said input channel, wherein the receiver unit includes an arrangement for coherently combining and processing signals representative of the ranging signals received by the antennas from each of a plurality of the transmitters, the arrangement advantageously includes a common signal processing channel including common filtering means to maintain phase coherence between output signals associated with any one of said transmitters, being signals extracted from the common channel and representative of the signals received at the antennas from that transmitter. Such apparatus can allow the individual adaptation of antenna array sensitivity pattern for each of the plurality of transmitters, irrespective of the line-of-sight directions of the other transmitter as viewed from the antennas.

Ranging signals may be received from remote transmitters in the form of earth-orbiting satellites, as in a GPS embodiment. Terrestrial systems are also possible, as are combined systems in which one or more of the transmitters is an earth-orbiting satellite, and one or more others are so-called "pseudolites" being transmitters which, in a GPS embodiment, transmits signals in the same format and at the same frequency as satellite-based transmitters.

The extent to which reception quality can be improved is influenced by the spacing of the antennas. In most embodiments, the antenna elements are much closer together than the GPS code phase wavelength (300 metres). However, the ranging signal wavelength at GPS is 19cms for the L1 transmissions. It follows that carrier phase outputs from different antennas spaced by distances of the same order will be different, giving the ability to weight and select signals for improved reception, as described above. However, the invention is not limited to apparatus having such antenna spacings. Advantages can be gained by placing the antennas with a spacing approaching the maximum possible afforded by the platform in question, such as at the front and rear of a motor vehicle. Advantages can be gained by having several antennas forming an array in which the inter-antenna spacing between neighbouring antennas is less than $\lambda/2$ where λ is the wavelength of the ranging signals in air, but with the

maximum span of the array greater than 5λ. In the general case, the antennas are spaced apart by 50mm or more to provide signals whose magnitudes are to some degree statistically independent.

5   Other aspects of the invention include receiving ranging signals via at least two antennas for independently sampling the local signal field, and employing a simple algorithm to select the largest signal from the two antennas, or to favour receiving direction to select transmitters having independent fading characteristics. Processing of the signals from each satellite is performed separately in choosing the selection or
10   weighting of the signals. Processing may be performed incoherently or coherently, the advantage of coherent processing being that it allows use of carrier phase differences between the signals received from individual transmitters at the different antennas to be employed in improving reception. Thus, application of a phase shift to one of the antennas may by used align its phase with that of the signal received at one of the other
15   antennas. A steering function may be applied in this way to the antenna signals with the maximum gain pointing in the direction of arrival of the required signal. This phase taper technique allows a 3dB improvement in the signal-to-noise ratio using two antennas.

20   As mentioned, above, both amplitude and phase taper may be used to maximise the signal extracted from the processor stages in the receiver unit. Both amplitude and phase taper functions may be changed dynamically to maintain the GPS signal from a chosen satellite at its maximum value, the amplitude and phase taper being adapted to the signal conditions.

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One other feature of the preferred embodiment of the present invention is the use of CDMA to pass GPS signals continuously through common parts of the receiver. This has the advantage of improving the signal-to-noise ratio of each of the satellite signals being observed. Furthermore, there is no requirement to select a master GPS signal; all
30   signals have equal importance.

One of the aspects of the invention referred to above is a special arrangement of antennas allowing discrimination between signals of different polarisation. Typically, the linear elements of the antenna referred to above consist of a pair of dipoles arranged in crossed format. Rather than connecting the elements to a coupling network to form a

5 combined antenna sensitive to signal fields with either left-hand or right-hand circular polarisation, in the present preferred embodiment, both antenna signals pass through the receiver unit and associated correlator structure phase coherently. Subsequent digital signal processing is arranged to sum the two antenna signals with either a plus 90° or minus 90° relative phase shift with the consequence that the receiver unit can be made

10 to choose either left-hand or right-hand circular signal polarisation. The alternative of making the system sensitive to elliptical polarisation, as referred to above allows any form of such polarisation to be accommodated by suitable choice of the gain relationship between the channels.

15 The invention will now be described by way of example with reference to the drawings in which:-

Figure 1 is a block diagram of a first GPS signal receiving system in accordance with the invention;

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Figure 2 is a more detailed block diagram showing reference and measurement channels of a receiver unit forming part of the apparatus of Figure 1;

Figure 3 is a block diagram of a second receiver system in accordance with the

25 invention;

Figure 4 is a block diagram of a third receiver system in accordance with the invention, having a common channel for signals emanating from a plurality of antenna elements;

30 Figure 5 is a block diagram of a fourth receiver system in accordance with the invention, designated particularly for mitigation of multi-path effects;

Figure 6 is a diagram illustrating the front end of the GPS receiver with a circuit for applying a phase taper; and

Figure 7 is a block diagram of a fifth receiver system in accordance with the invention

5   for selecting circularly or elliptically polarised signals.

Referring to Figure 1, in a first embodiment of the invention, multiple antenna GPS

10   receiver apparatus has a multiple antenna array 10 comprising a number of antennas in a spaced-apart arrangement. The array is coupled to a receiving unit 12, each antenna feeding signals to a respective input stage 14 of the receiver unit 12. Each input stage 14 has filtering and amplifier elements 14A, 14B, a down-convertor 14C and an analogue-to-digital converter (ADC) 14D. One of the antennas is selected as a

15   reference source, the corresponding output 16 being coupled to a number of reference channels 18, each of which is arranged to process the signals from a respective visible member of the GPS satellite constellation. In Figure 1, four reference channels are shown, but it will be appreciated that different numbers of reference channels may be established according to the number of satellite transmitter signals to be processed. The

20   signals from the other antennas, after amplification, down-conversion and digitisation in the respective input stages 14, are fed to measurement channels 20, at least one for each received satellite signal at each antenna other than the reference antenna, so that each measurement channel processes a signal representative of the input signal from one satellite as received at one respective antenna. The outputs from the measurement

25   channels are representative of the carrier phase of each transmitter at each antenna.

Referring to Figure 2, in each reference channel code and carrier tracking loops are established for each visible member of the satellite constellation. The code and carrier loops include code and carrier replica generators which are used in a product or

30   correlation detection arrangement. In this example, the reference channel has a correlator stage 24 with four correlators each having input mixers, and an integrator. A first pair of correlators 26 operates on an on-time version of the code replica and

in-phase and quadrature versions of the carrier replica. The other pair 28 of correlators operates on a composite version of the code replica formed from the early and late components of the code, each member of the pair operating on versions of the carrier replica which are in phase and quadrature. Referring to Figure 2, the code replica is

5   formed in a conventional manner by feeding the outputs of the integrators in the second pair 28 of correlators to a delay locked loop 30 and thence to a delay locked loop filter 32 which controls a numerically controlled oscillator 34. This acts as a clock for a pseudo random bit sequence code generator 36 for generating on-time (OT) and early-minus-late (E-L) versions of the code for the satellite signal being received via

10   input 18A. As will be seen from Figure 2, the OT and E-L versions of the code are fed to input mixers 38, 40 for the carrier loop and code loop respectively.

The first correlator pair 26 feeds a phase detector 42 producing a signal representative of carrier phase which is then filtered by a carrier loop filter 44 for controlling a second

15   numerically controlled oscillator 46. This NCO 46 is arranged to produce quadrature outputs as a carrier replica for feeding two further mixers 50 in the correlator pairs 26, 28, as shown.

The tracking loops settle with code phase and carrier phase estimates appropriate to the

20   selected satellite and antenna combination.

As one alternative, the reference channel may have six rather than four correlators, one operating on an early version of the code replica and the other on a late version.

25   The individual antenna elements of the array 10 are normally close together, as measured on the scale of a GPS code phase wavelength (300m). However, carrier phases for outputs from other antennas, but for the same satellite, are different since the antenna element spacing is on the same scale as the carrier wavelength (19cm for L1 in GPS). The measurement channels 20 for these antenna-satellite combinations are

30   established to receive the code and carrier replicas generated in the reference channel 24. Accordingly, referring to Figure 2, only the on-time (OT) code version from the coder 36 is applied to the measurement channel 20, together with the quadrature and

in-phase carrier replica versions. Each measurement channel 20, then, has a correlator pair 52 with integrators which feed a carrier phase detector 54 producing a signal representing the phase of the particular antenna-satellite combination for that channel (at output 20A). By using the on-time code replica version and carrier replica signals

5   from the reference channel 18 for a particular satellite, the measurement channels corresponding to the same satellite operate at least approximately at the peak value of the code correlation function. However, the carrier phase measurements are different to the extent of the resolved line-of-sight differences between the reference antenna and the other antennas of the array 10. The outputs 20A (see Figure 1) from the in phase

10   and quadrature correlator channels are connected to feed $\tan^{-1}$ representations to a combiner 58 the output of which is a spatially filtered representation of the signal from the corresponding satellite.

The combiner 58, in its simplest form, forms the sum of the input antenna

15   measurements after they have been multiplied by amplitude and phase taper functions. The choice of the phase and amplitude multiplication coefficients determines the spatial filtering characteristic. A least-mean-square (LMS) algorithm, for example, may be used to maximise the signal-to-noise ratio at the combiner output 58A. If an adaptive equaliser is used to determine the phase and amplitude tapers, the early stages of

20   adaptive processing are likely to be characterised by noise reduction subject to certain directional gain constraints rather than signal enhancements.

As will be seen, the arrangement described above with reference to Figures 1 and 2 has two particular architectural characteristics:-

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        (a) the antenna array processing is performed entirely in the digital
        processing section of the GPS receiver, and
        (b) the antenna array processing and the related spatial gain pattern can
        be different for each satellite in the GPS satellite constellation.

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An alternative receiver system embodying principles similar to those contained in the apparatus of Figure 1 is shown in Figure 3. This embodiment is in the form of a

two-channel satellite positioning system receiver featuring antenna diversity. It will be appreciated, of course, that the illustrated arrangement can be expanded to receive signals from more than two antennas.

5   This system has two antennas 101,102 which are coupled to two front end receiver circuits 103, 104. The front end receiver circuits are not completely independent in that, in one preferred embodiment, they share common local oscillator signals derived from a fixed frequency synthesizer circuit 105. The synthesizer circuit 105 is coupled to a reference oscillator 106 of fixed frequency. Down-conversion of the received

10   satellite signals takes place in each of the receiver circuits to an intermediate frequency (i.f.) at which the signals are sampled in time and digitized in ADCs 107, 108. The outputs of the ADCs are coupled to further down-converters 109 to 112 which are connected to variable frequency sources 113 and 114. Each ADC therefore yeilds two output signals which have been sampled in time so that the resulting i.f. samples are

15   substantially separated by 90 degrees in phase, the signals 113, 114 having identical frequencies but differing in phase by substantially 90 degrees. The signals 113, 114 are formed in a signal generator 115 which has a control input 116. The outputs of the four further down-converters 109 - 112 are combined in sideband canceller circuits 117, 118 to substantially remove the unwanted sideband formed in the outputs from

20   down-converters 109 - 112. The output of the second down-conversion step is at base-band. The outputs of the sideband cancellers 119 – 122 are representations of the in-phase and quadrature base-band equivalents of the two received satellite signals.

The outputs of the sideband canceller circuits are coupled to code a plurality of

25   de-spreading circuits 123. The de-spreading circuits are coupled to a source 124 of code replica signals representative of the signals emitted from the satellites. As in the previously described embodiment, a multiplicity of versions of the replica signals are generated with the feature, in this GPS embodiment, of having different delays in the range to the satellite. Pairs of replica signals are coupled to integrator units 125, which,

30   along with the replica signal generator 124, form a circuit whose output signals are representations of the cross-correlation of the received signal with the signal replicas. This circuit, therefore, substantially performs the function of a matched filter which is

matched to the satellite transmitted signal. The outputs of the two integrator units 125 are combined in each channel in respective first combiners 126 to produce a control signal component for a particular respective antenna-satellite combination.

5   During the process of signal acquisition, the signal replica generator is approximately aligned with similar signals arriving from the satellite. The multiplicity of signals is used initially to make approximate estimates of the range to one of the satellite signal sources. The outputs of each integrator pair responds each of the replica signals to make different representations of the cross-correlation co-efficient. By appropriate

10   combination of the respective control signal components, these signals form a control signal to adjust the signal replica generator so that a chosen signal replica is aligned with the received satellite signal, or to form a control signal so that the phase of the carrier signal replica generator 115 can be brought into phase alignment with the received signal.

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Accordingly, similar outputs from the two channels are fed into a combining circuit 127 which is coupled to a control system 128 which is, in turn, coupled to the signal replica generator 124. The action of the control system 128 is to maintain the alignment of the signal replica circuit 124 in the first instance. This second combiner 127 is used to join

20   the outputs of the two receivers and is also coupled to a control system 129 whose function is to maintain the phase of the carrier replica signal approximately the same as that from the two antennas.

The circuits 126, 127 combining the outputs from the channels coupled to the two

25   antennas may take several forms. The simplest embodiment is a circuit which forms the weighted sum of the two signals. The weighting function may be derived from the signal-to-noise ratio of each antenna channel or may be used to selectively couple just one of the channels to the input of the control system or systems.

30   As will be understood from the indication of parallel outputs 130 from the sideband cancellers 117, 128 in Figure 3, separate pairs of correlators and subsequent control

systems are established for the received signals of each of a number of satellites to be employed.

In order for the phase measurements for each antenna element to be truly phase
5   coherent, it is desirable for the gain, filtering and down-conversion processes to be identical for each antenna channel. This is difficult to achieve in separate receivers but can be partially arranged using local oscillators for the down-conversion stages. However the gain and phase signatures and variations induced in the signals by non-identical filters and amplifier stages are difficult to control.

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Referring to Figure 4, a simple solution uses identical circuits to provide for the gain, filtering and down-conversion for all antenna circuits. In this arrangement, the separate antenna circuits are code-division-multiplexed prior to most of the radio frequency (r.f.) and intermediate frequency (i.f.) processing. In the example shown, only the front end
15   filtering and low-noise amplifier units 150A, 150B are individual to each antenna element 10A. Stable gain or phase variations from channel to channel would, in an adaptive system, be removed by adapting to a specific performance attribute. However, variations in group delay signatures would not be removed by this form of adaptive processor. This is where the spread spectrum properties of code-division multiplexing
20   shows a clear advantage over time division multiplexing (which degrades signal to noise ratio) and frequency division multiplexing (which renders imperfect group delay signatures).

As shown in Figure 4, the front end antenna circuits 150, of which there is one for each
25   antenna, contains a bandpass filter 150A and a low-noise amplifier 150B. In each circuit these feed mixer stages 150C where, in each channel, the antenna signal is multiplied by a respective multiplier signal obtained from a PRBS (pseudo random bit sequence) code generator 153. Since the code generator 153 has an output K for each antenna circuit K, and each output from the generator 153 generates a different code
30   signal, the product outputs from the mixers 150C are each coded with a respective code which serves to identify the received signal when they are subsequently combined in adder 155. In this embodiment, the codes from the code generator 153 are pseudo

random spreading codes all having a common bit rate, and each is superimposed using mixers 157 (one for each antenna circuit), with a local oscillator signal from a local oscillator source 159 common to the plurality of antennas circuits. Accordingly, the mixers 150C serve as down converters, converting the received signals to an

5   intermediate frequency.

The summed i.f. signal from the output of the adder 155 is then fed through a common receiver channel consisting of an i.f. bandpass filter 161 and amplifier 163, whereafter the i.f. signal is digitised in ADC 165. At this point, as is the case with digital signals

10   in each of the embodiments described in this specification, it is possible to process the signals using hardwired logic or software, and the associated diagrams and description are to be interpreted as covering both alternatives, including a combination of the two. Referring again, then, to Figure 4, the output of the ADC 165 is fed to a plurality of channels 167, one for each antenna, each containing a mixer 167A which receives the

15   same respective code as that applied in respect of the relevant antenna in mixers 150C. This has the effect of isolating the representation of the respective received signal at the output of the mixer 167A, this output representation then being split into plural sub-channels 169 corresponding to the satellites from which signals are received. As a result of the common processing of the antenna signal representations in the common

20   i.f. channel, phase coherence for the signals received from each satellite at the different antennas is substantially maintained, yielding improvements in carrier phase measurement and discrimination.

Other embodiments of the invention may use multiple antennas but with different

25   processing algorithms. Spatial diversity processing allows systems to survive certain forms of interference. If the antenna elements are spaced moderately closely with inter-element distances of the order of several wavelengths, it is usually possible to provide some protection against propagation path fading. This is determined by the ambiguity function of the transmission channel which exhibit spatial, temporal and

30   frequency coherence. Providing the antenna element spacing is greater than the spatial coherence distance, the antennas receive signal versions subject to statistically independent path configurations.

A simple algorithm which can be used to gain some benefit from spatial diversity simply selects the (antenna) channel exhibiting the largest output signal. Channels with deep amplitude fades are excluded from making a contribution to the signal.

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The optimum processing for randomly fading channels with a Rayleigh distributed amplitude probability density function is well known. The processor requires the summation of the weighted power from each channel. The optimum weighting is the 'a priori' signal to noise ratio. If, for instance, in a multi-path reception area, the channels

10   support some portion of the direct path satellite signal, the amplitude distribution becomes Ricean (i.e. with one dominant component). The optimum processor is more complex in this case and, where possible, forms the coherent sum of the stable phase parts of the signal.

15   Such a system may be applicable to the more complex GPS processors in situations where the propagation path from the satellite is subject to significant fading behavior. Inside buildings, GPS signal reception is dominated by multi-path propagation with significant fading. An adaptive processor as described above offers the possibility of acceptable results in the variety of situations from direct signal path reception to

20   multi-path dominated signal behaviour.

This concept is particularly applicable to mobile systems where the spatial and temporal signal fields have significant variation. It is more difficult to implement this in hand-held equipment due to the small physical size of the device in comparison with

25   the coherence distance of the spatial signal field. Data relating to the signal ambiguity function in a variety of situations indicate that coherence distances of the order of 50cm inside buildings may be expected. This is in accordance with the above-stated concept of signal interference on the scale of the GPS carrier wavelength. It will be appreciated, therefore, that implementation of spatial diversity is more applicable to vehicular

30   applications due to the wider potential spacing of the antenna elements. The requirement for multiple antennas and the consequent need for coaxial cable connections within the vehicle is mitigated by printing the antennas on the rear screen

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and by locating at least a portion of the receiver unit in close proximity to the antenna output terminals.

Multi-element antenna systems have been described hereinbefore as a means to reduce multi-path signal propagation effects in ranging systems. It should be understood that this technique is useful in, at least, survey and timing applications of GPS as well as position-fixing.

Alternative signal processing arrangements will now be described. Referring to Figure 5, an antenna arrangement comprises a two dimensional array 10 of n^2 elements coupled through individual low-noise amplifiers (LNA's) to first down-converters. The simplest system arises when the antenna elements are uniformly spaced. Each down-converter 212B is driven by a common local oscillator 213 modulated with a distinct code chosen from a set of circularly non-correlated pseudo-random sequences, the code signals being derived, as in the embodiment of Figure 4, from a multiple output code generator 215 and combined by respective mixers 217 with the local oscillator signal. Gold codes are well known examples of such sequences exhibiting bounded out-of-phase auto-correlation and cross-correlation properties. Gold codes with sequence lengths greater than 1023 are known and have the benefit of reducing the signal leakage between different sequences (or virtual antenna channels).

This, and subsequent processing elements are shown in Figure 5, which is self-explanatory in the light of the following description and the above description of the other embodiments of the invention.

The dimensions of the antenna array 10 are small compared with the code wavelength of 300m but large compared with the carrier wavelength. The inter-element spacing may take a range of values, but there is much to support the application of the Nyquist sampling theorem applied spatially. This requires that samples of the signal field must be taken with inter-element spacing of less than $\lambda/2$. The physical extent of the array is one of the design choices within the scope of the present invention and is related to the coherence distance of the GPS signal field derived from the scattering function. The

antenna structure will be ineffective in reducing multi-path propagation effects if the array size is smaller than the coherence distance – longer arrays have smaller beam-widths (or circles of confusion if expressed optically).

5   Either a reference channel 220 (processing signals from a selected antenna, as described above with reference to Figures 1 and 2), or a combination of channels, is used to generate a code-tracking signal using an early-minus-late (E-L) code replica. One such reference channel (220) is provided for each satellite to be tracked. The code modulation is removed from the antenna processing channels by multiplication with an

10   on-time (OT) code replica.

In this form, a large number of processing channels is required – of the order of $m \times n^2$, where m is the number of satellites to be tracked. However, the analysis effort can be reduced. One method for processing the output of an antenna array uses a Fourier

15   Transform to convert the spatial samples into angular samples. Each such angular sample simply represents a beam pointing in one of directions defined by the transform. The beams have the characteristic of a linear summation of the antenna element outputs pre-multiplied by a linear phase taper. The beam patterns are mutually orthogonal as in classic Fourier Transform theory. There are many alternatives to the Fourier Transform

20   processor, such as the generalised two-dimensional Karhunen-Loeve Transform.

The operation of each satellite processor may be viewed as a spatial filtering operation, in which, for non-adaptive processors, the signal beam containing the least disturbance from multi-path propagation is selected for code measurements and carrier tracking.

25   For adaptive processors, the antenna element pre-multiplier (a linear phase taper for the example described above) is replaced with an amplitude and phase weighting function prior to antenna signal combination. Often, the simplest from of combiner is used (a summation device), however, other forms are possible. One combiner divides the antenna into two sub-arrays whose elements are summed. The output of the combiner

30   is formed as the product of the two sub-array outputs.

The spatial correlation function for a statistical average of a multi-path situation is defined as $\Re(\theta,\Phi)$. This is the equivalent of a communication channel scattering function (the transmission path from satellite to user receiver may be viewed as a communication path). A simple array-processing scheme is depicted in Figure 6. In this system, each antenna element in the array 10 is weighted by a linear phase taper of α_e per element in the x-direction, β_e in the y-direction and with uniform amplitude weighting. This causes a beam to be steered in a direction (θ_e, ϕ_e) to the normal of the array. The beam pattern is $U(\theta,\phi)$:

The spatial auto-correlation function for the array output is $\Phi(\theta)$:

$$\Phi(\theta) = U^*(\theta,\phi). \ U(\theta,\phi).\Re(\theta,\phi) \text{ where } U^*(\theta,\phi) \text{ is the complex conjugate of } U(\theta,\phi).$$

In most situations, this lower multi-path propagation disturbance if the peak in $U(\theta,\phi)$ selects substantially the direct path signal from the satellite. This is represented in $\Re(\theta,\phi)$ as a peak in (θ,ϕ) corresponding the satellite transmitter (SV) direction whereas multi-path propagation effects form a 'halo' effect (statistically) around the peak.

Referring to Figure 7, as a further embodiment of the invention, a GPS receiving system has a GPS crossed dipole arrangement 10 with each dipole connected to a respective input channel 250 in an arrangement analageous to that shown in Figure 4. The two antenna signals are coupled through a common radio frequency (r.f.) and intermediate frequency (i.f.) processing assembly 252, as in the Figure 4 embodiment, which provides phase and group delay stable amplification, filtering and down-conversion. One way to provide for such processing is by means of code division multiplexing for two channels through a common hardware r.f. processor (see PRBS code generator 254 and associated mixers 255). Each channel is attached to a separate antenna element. Again as described and shown already, in the digital processing section of the GPS receiver the code division multiplex signals are separated into two channels (256, 257)again. Code and carrier tracking channels, including carrier and delay locked loop processors (260, 261), are formed for each decoded antenna channel. The code loop

tracking positions are the same for each antenna. The carrier tracking loops produce phase and frequency estimates for the implicit GPS carrier signal.

Performance benefit may be taken by forming a single code tracking loop which is
5   driven from a code phase error signal derived from both channels. Similarly, the carrier signal tracking loops share a common frequency but have different phases depending upon the direction and type of received signal. By forming the coherent sum and difference of the two (equally weighted) on-time signals from the carrier channels, both right and left hand circularly polarized receptors may be formed. This is representative
10   of the behaviour of a network located at the antennas which forms the sum and difference of the two received signals as shown in Figure 7.

The performance attributes, which accrue from the digital implementation, are severalfold. These include a lack of network-induced antenna coupling, precise control
15   of amplitude and phase of the coupling network, use of unequal weighting factors – allowing to elliptical polarization antenna structures, and adaptive control of the phase and amplitude weighting parameters, which provides near-optimum processing with uncertain and/or unstable signal polarization.

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Claims

1.   Apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system, wherein the apparatus comprises a radio receiver unit having a plurality of radio frequency (r.f.) input connections, and a plurality of spaced-apart antennas each connected to a respective said input connection, and wherein the receiver unit includes:-

an antenna signal processing circuit responsive to the ranging signals for producing output signals including components each individually representative of at least one characteristic of the ranging signals received at a respective antenna, and

a signal preferment arrangement configured to yield a range estimate by receiving the output signals, monitoring for each of a plurality of the said remote transmitters, at least one characteristic of the ranging signals from that remote transmitter via the different antennas, and varying the relative extent to which the said components are used to yield the range estimate.

2.   Apparatus according to claim 1, wherein the signal preferment arrangement is a signal combiner configured to receive the output signals, to monitor, for each of a plurality of the said remote transmitters, at least one characteristic of the ranging signals from that remote transmitter via the different antennas, and to weight one or more of the said components to yield the range estimate.

3.   Apparatus according to claim 1, wherein the signal preferment arrangement is a signal selection arrangement configured to receive the output signals, to monitor, for each of a plurality of the said remote transmitters, at least one characteristic of the ranging signals from that remote transmitter via the different antennas, and to select one or more of the said components to yield a range estimate.

4.   Apparatus according to any preceding claim, wherein the signal preferment arrangement is configured to weight or select the components according to the signal-to-noise ratios of the ranging signals received from at least one of the transmitters at the different antennas.

5.   Apparatus according to claim 3, wherein the preferment arrangement is configured to weight or select the components associated with the different antennas according to signal-to-noise ratios of the ranging signals from each of the transmitters.

6.   Apparatus according to any preceding claim, wherein the signal preferment arrangement is configured to weight or select the components according to the amplitudes of the ranging signals.

7.   Apparatus according to any preceding claim, wherein the antenna signal processing circuit includes at least one code-tracking loop for tracking code modulation of the said ranging signals when received by the antennas.

8.   Apparatus according to claims 3, 6 and 7, wherein the signal selection arrangement is configured periodically to select one of the said ranging signals, the amplitude of which is greater than that of the other ranging signals or at least one of the other ranging signals, and to apply the selected signal to the code tracking loop.

9.   Apparatus according to claim 7, having a plurality of code tracking loops, wherein the signal selection arrangement is configured periodically to select a plurality of the said ranging signals by weighting the magnitudes of the ranging signals according to a predetermined weighting scheme.

10.   Apparatus according to claim 6, wherein the weighting scheme is dynamically variable.

11.   Apparatus according to claim 1, wherein the signal preferment arrangement is configured to weight or select the said components according to the multi-path content of the ranging signals received via the respective antennas.

12.   Apparatus according to any of claims 1 to 3, including a parallel correlator structure.

13.   Apparatus according to any preceding claim, wherein the receiver unit further comprises:-

a carrier phase tracking loop, and

5   a phase-shifting arrangement operable to apply a selected phase shift to a selected or weighted signal, the magnitude of the phase shift being dynamically adjusted according to the antenna via which the selected or weighted signal is received.

14.   Apparatus according to claim 13, wherein the phase-shifting arrangement is 10   configured to adjust the phase shift in a manner such as to maintain coherent phase matching between ranging signals received via the different antennas.

15.   Apparatus according to claim 13, wherein the phase-shifting arrangement is configured to adjust the phase shift in a manner such as to maintain coherent phase 15   tracking while switching between different selected ranging signals from different antennas.

16.   Apparatus according to any preceding claim, wherein the receiver unit includes an adaptive equaliser arranged to set phase and/or amplitude taper multiplication 20   coefficients for application to the ranging signals from the different antennas.

17.   Apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system, wherein the apparatus comprises a radio receiver unit having a plurality of r.f. input channels and a 25   plurality of spaced-apart antennas each connected to a respective said input channel, wherein:-

the receiver unit includes at least one antenna signal processing circuit responsive to the carrier phases of the ranging signals received via at least one of the antennas,

30   each input channel i includes a multiplying element arranged to combine a respective first multiplier signal M_i with an incoming signal in the channel, the multiplier signals constituting an orthogonal set of signals, and

the receiver unit further includes a combining element for combining the multiplier output signals resulting from combining the incoming signals with the multiplier signals, a common intermediate frequency channel including common filtering means for receiving the multiplier output signals from the combining element,

5   an analogue-to-digital converter (ADC) coupled to an output of the common channel, and a processor for applying second multiplier signals to a digitised signal obtained from the ADC thereby substantially to isolate from each other signals representative of respective incoming signals from respective antennas, each second multiplier signal corresponding to or being the same as the first multiplier signal for the respective

10   antenna,

whereby phase coherence is maintained between the different signals associated with the different antennas.

15   18.   Apparatus according to any of claims 1 to 3 or 17, wherein the antennas have different polarisation characteristics, and wherein the processor is programmed to combine the digitised representations of the different antenna signals to weight or select received signals having a predetermined polarisation.

20   19.   Apparatus according to claim 18, wherein the antennas comprise a pair of antennas each formed as a linear element, the linear elements being arranged perpendicularly to each other so that, according to the way in which the digitised representations of the signals are combined, the receiver unit selects received signals of right-hand circular polarisation or left-hand circular polarisation.

25   20.   Apparatus according to any of claims 1 to 3 or 17, wherein the antennas comprise a pair of antennas each formed as a linear element, the linear elements being arranged perpendicularly to each other, and wherein the processor is programmed to weight and combine the digitised representations of the different antenna signals in order to select received signals of elliptical polarisation.

30

21.   Apparatus according to claim 19 or claim 20, wherein the processor is configured to implement sum and difference networks.

22.   Apparatus according to any of claims 18 to 21, wherein the processor is programmed so as to combine the digitised representations variably.

23.   Apparatus according to claim 22, wherein the processor is programmed so as to combine the digitised representations in an adaptively varying manner in order to optimise signal reception in a multipath environment.

24.   Apparatus according to claim 17, wherein the processor is programed to apply selected weightings to the isolated signals in order to tailor the response of the receiver unit to favour received signals having a predetermined characteristic.

25.   Apparatus according to claim 24, wherein the weightings are adaptively variable.

26.   Apparatus according to claim 17 and any of claims 18 to 25, wherein the receiver unit has input channels which include a pair of sub-channels for I and Q components of the respective incoming signal, and wherein the processor is programmed to combine the said I and Q components after isolation of the signals representative of the incoming signals.

27.   Apparatus according to claim 17 and any of claims 18 to 25, wherein the multiplying element is arranged to combine a respective spreading code A_i with the incoming signal in the channel and the processor is arranged to apply corresponding despreading codes B_i to the digitised signal obtained from the ADC for extracting the signals representative of the incoming signals from the respective antennas.

28.   Apparatus according to any preceding claim, arranged to receive ranging signals from remote transmitters which include at least one earth-orbiting satellite.

29.   Apparatus according to claim 28, arranged to receive ranging signals from remote transmitters all of which are earth-orbiting satellites.

30.   Apparatus according to any preceding claim, wherein ranging signals have a wavelength λ in air and form an array having a maximum dimension greater than 5λ.

5   31.   Apparatus according to claim 30, wherein the array comprises at least three antennas and the inter-antenna spacing of at least a pair of the antennas is less than or equal to $\lambda/2$.

32.   Apparatus according to any preceding claim, wherein the antennas are spaced
10   apart by distances of at least 50mm.

33.   A vehicle including apparatus according to any preceding claim, the antennas being mounted in different parts of the vehicle.

15   34.   A vehicle according to claim 33, including at least three antennas connected to the receiver unit, one mounted in each of two door or wing mirror housings, and one in a rear part of the vehicle.

35.   A vehicle according to claim 34, including at least one antenna mounted in or
20   on the vehicle windscreen.

36.   Apparatus arranged to receive ranging signals produced by a plurality of remote transmitters which form part of a universal ranging system, wherein the apparatus comprises a radio receiver unit having a plurality of radio-frequency (r.f.)
25   input channels, and a plurality of spaced-apart antennas each connected to a respective said input channel, wherein the receiver unit includes an arrangement for coherently combining, processing and separating signals representative of the ranging signals received by the antennas from each of a plurality of the transmitters, the arrangement including a common signal processing channel including common filtering means to
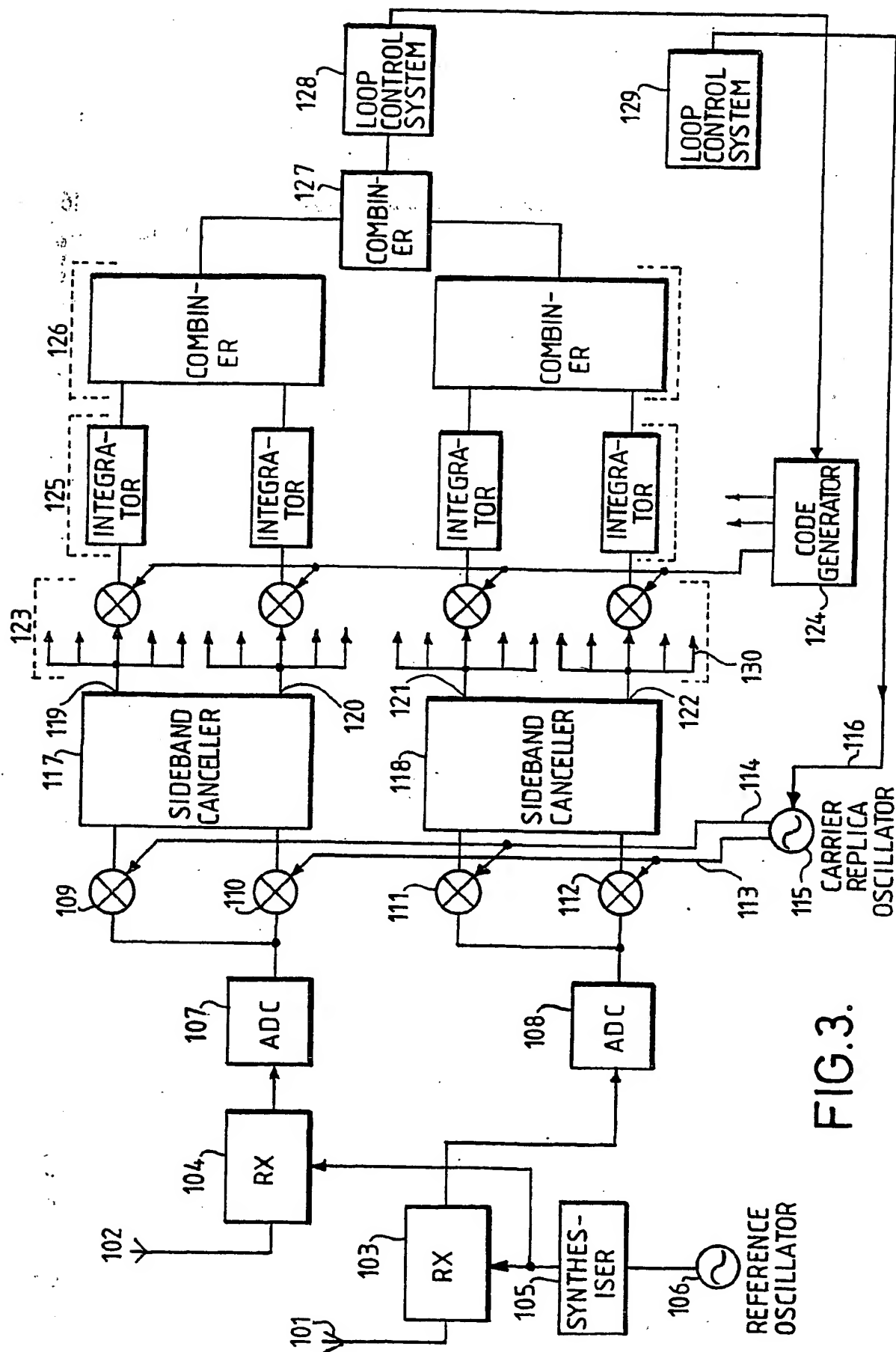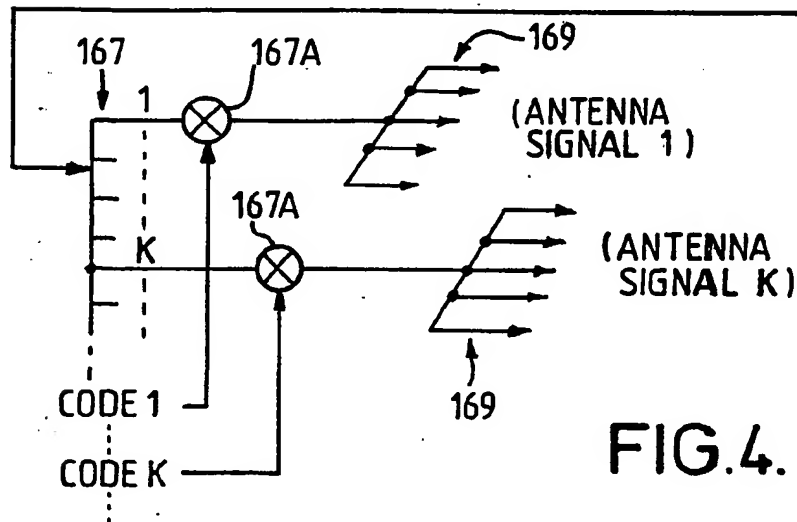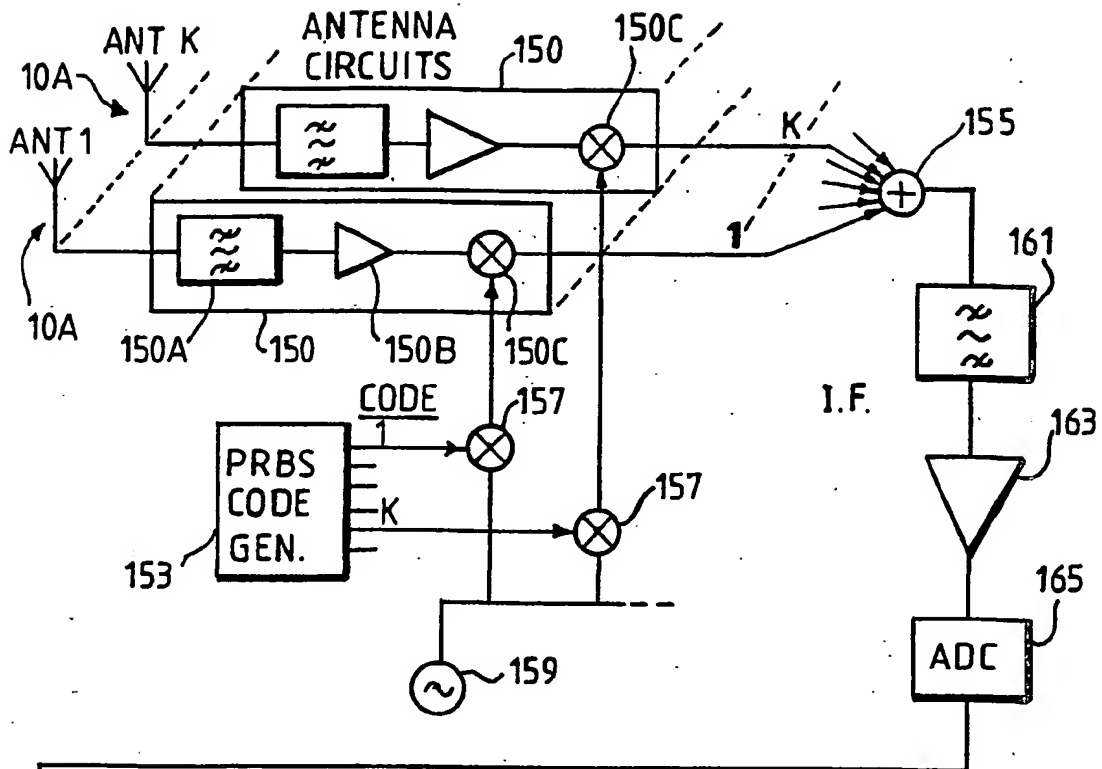30   maintain phase coherence between the separated signals associated with any one of said transmitters.
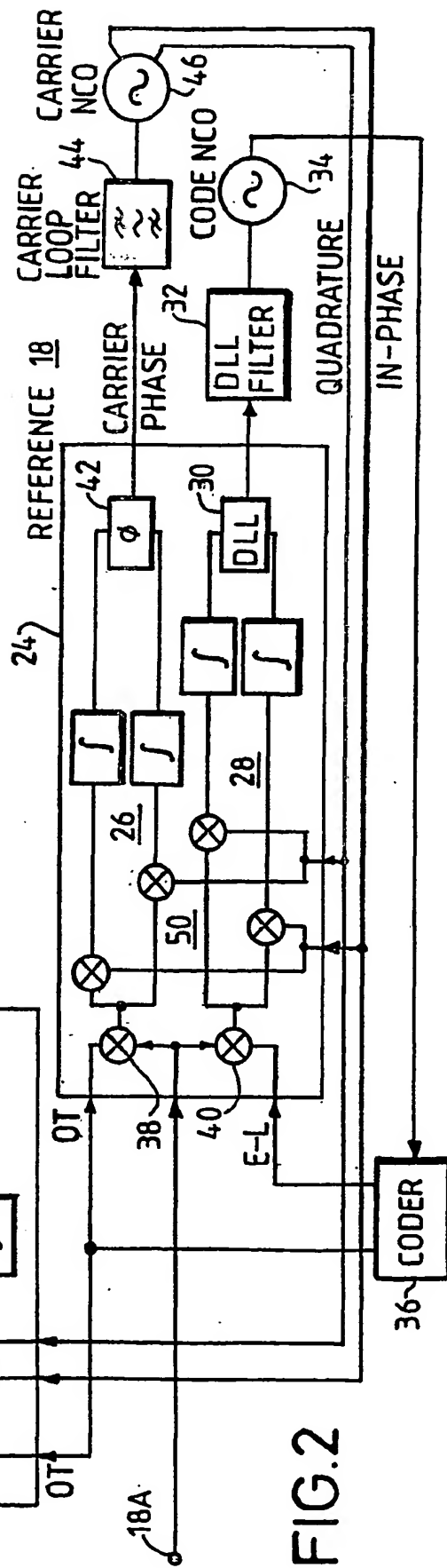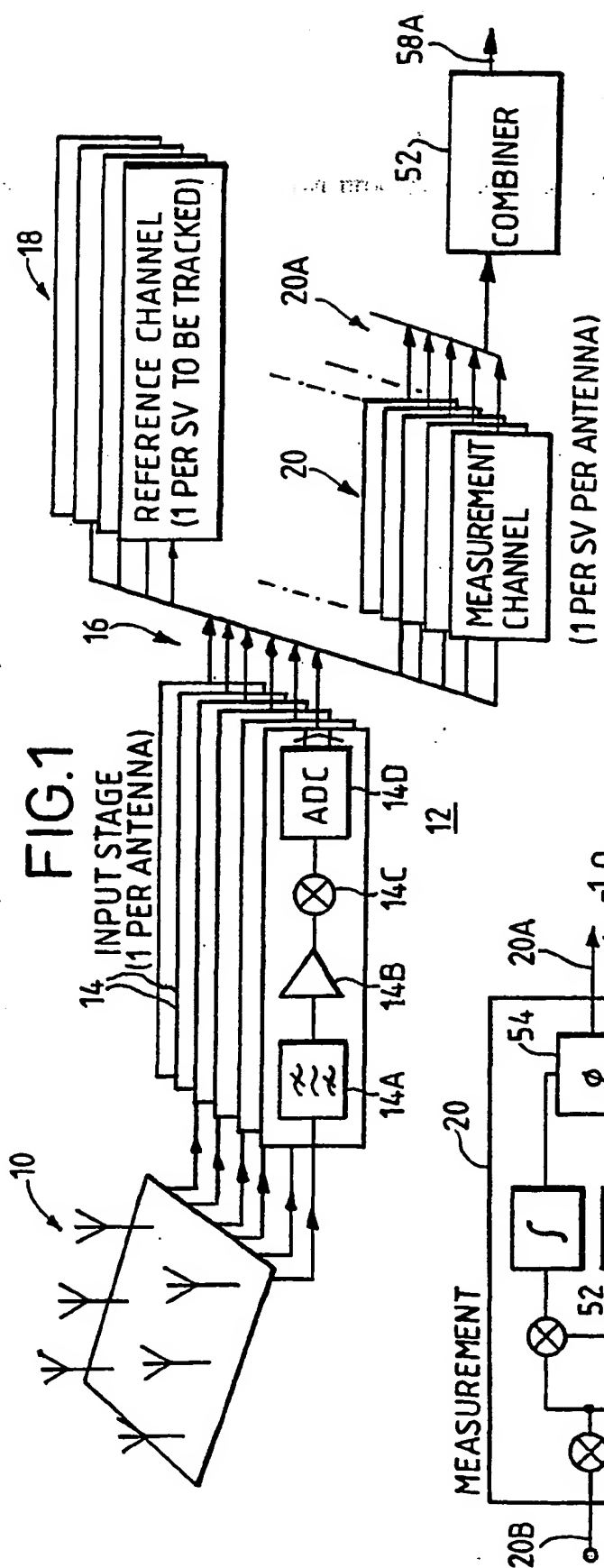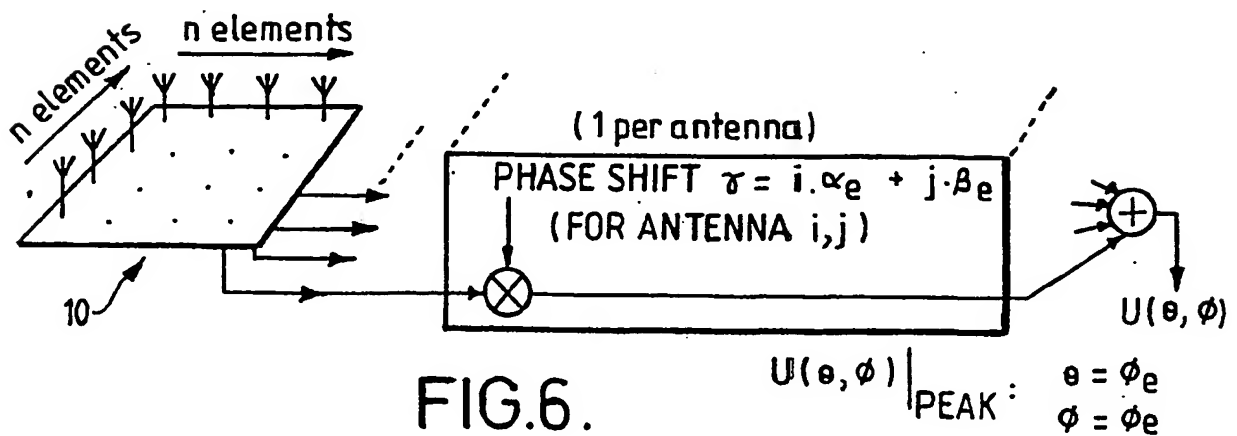
FIG.1
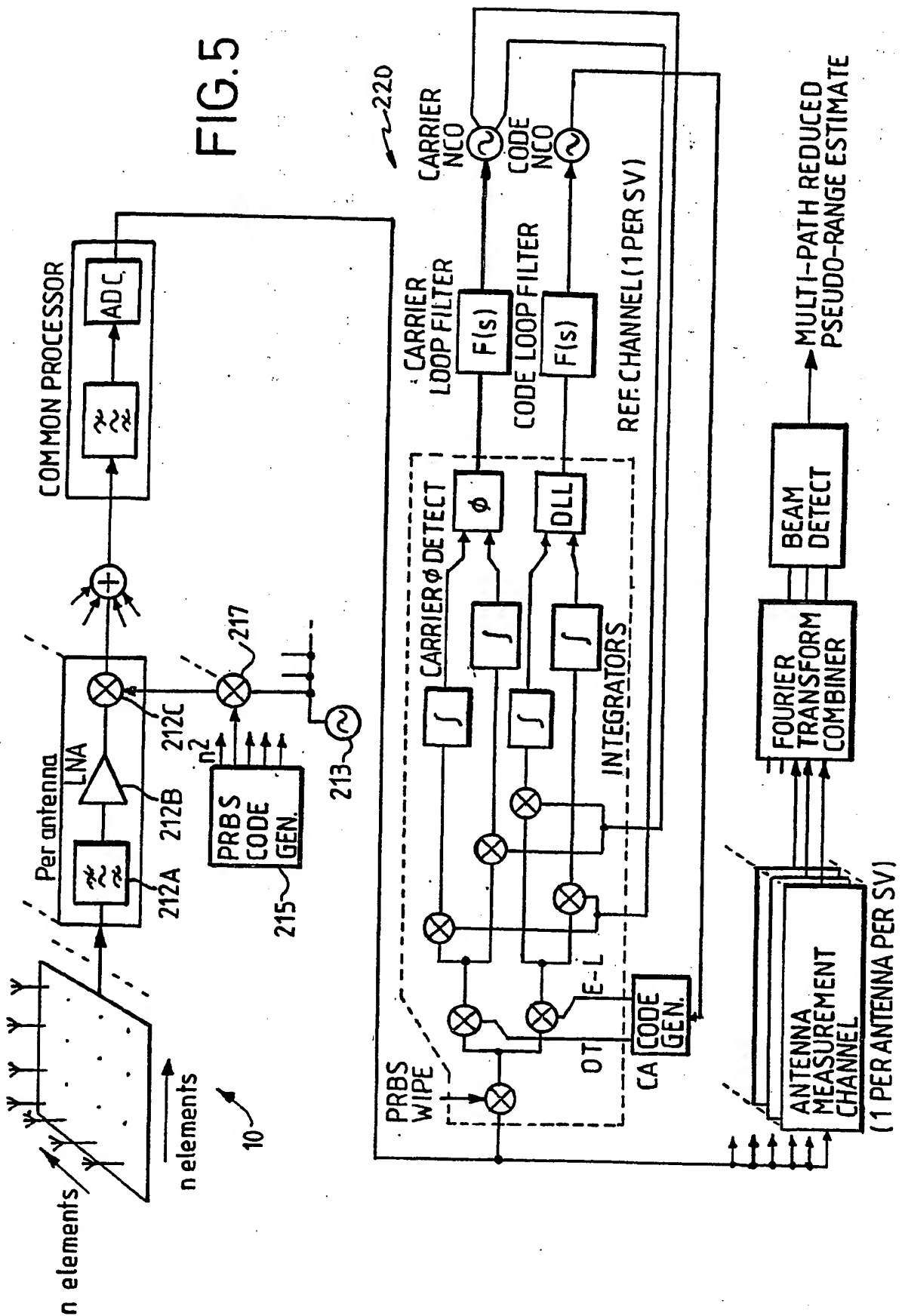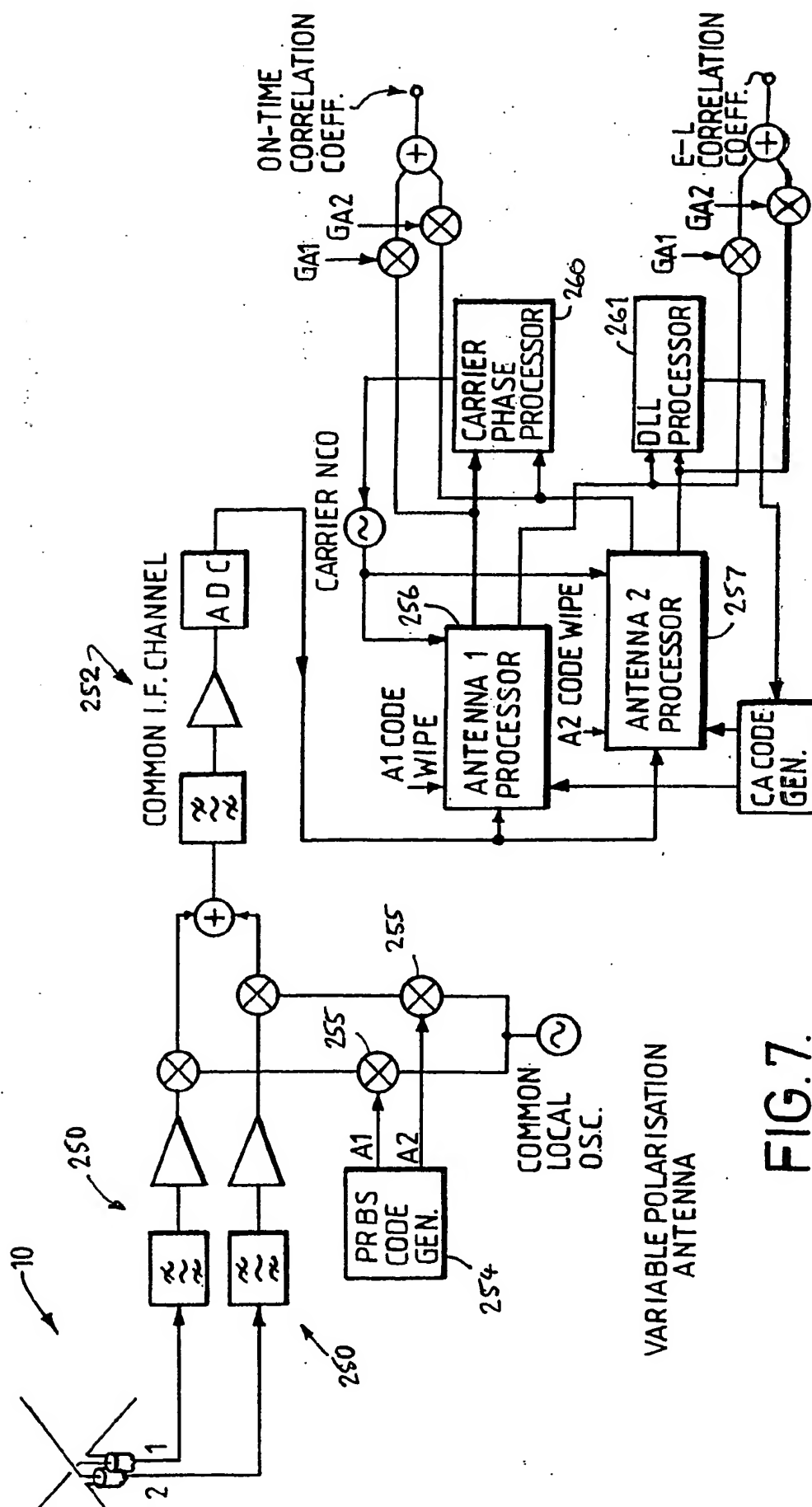
FIG.2

FIG.3.

FIG.4.

FIG.6.

FIG.5

FIG.7.

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01S1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7   G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 952 968 A (MCDOWELL CHARLES E) 14 September 1999 (1999-09-14) abstract; figures 1,2	1-16
Y		17-36
X	US 5 917 446 A (GREENSPAN RICHARD L) 29 June 1999 (1999-06-29)	1
Y	column 4, line 66 -column 11, line 45; figures 1-3	2-36
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Y	column 1, line 65 -column 2, line 54; figure 1	2-36
X	US 6 114 988 A (VALLOT LAWRENCE C ET AL) 5 September 2000 (2000-09-05)	1
Y	column 13, line 22 - line 60; figures 1,3	2-36

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 February 2002	2 1. 02. 02

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340-2040, Tx. 31 651 epo nl.	

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 990 831 A (MCDOWELL CHARLES E) 23 November 1999 (1999-11-23)	1
Y	column 1, line 66 -column 4, line 17; figures 1-3,7	2-16
Y	DE 42 23 676 A (SIEMENS AG) 20 January 1994 (1994-01-20) page 1, line 50 -page 2, line 4; figure 1	1-16
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Box I   Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
   because they relate to parts of the International Application that do not comply with the prescribed requirements to such
   an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II   Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this International application, as follows:

     see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all
      searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment
      of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report
      covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is
      restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest   ☐ The additional search fees were accompanied by the applicant's protest.

                                   ☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM   PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-16

    Receiver for receiving and weighing multiple ranging signals received from a plurality of antennas

2. Claims: 17-36

    Receiver for receiving multiple ranging signals received from a plurality of antennas, whereby each antenna signal is spread using a first multiplier and one of a set of orthogonal codes allocated to the individual antenna signal, the spreaded signals from all antennas are combined to generate a common intermediate signal, and finally, prior of processing, an individual antenna signal is isolated from the other superposed signals using a second multiplier and the allocated code of the antenna signal for despreading the signal.